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Role of Chemical Effects in Daytime High Latitude Trough Formation

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The role of enhanced chemical reaction rates in the formation of the daytime F-region trough is examined. A simple convection model is used to estimate the maximum likely elevation of effective temperature for the ion reaction $O^+ + N_2 \rightarrow NO^+ + N$. Under extreme conditions the effective temperature can reach 4000 K resulting in a 30-fold increase in the reaction rate. However, the resulting reduction in F-region electron density is only a factor of 4. Under more usual conditions, the reduction is less than a factor of 2. The actual density reduction factor in the daytime trough is observed to vary between 3 and 10 under normal conditions. Therefore, we conclude that under most circumstances, convection-enhanced chemistry contributes very little to the formation of the daytime trough.

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Preface

We wish to thank Dwight Decker for providing the calculations whose results are displayed in Figure 3.

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1. INTRODUCTION

The phenomena of high latitude, F-layer troughs have been observed and studied for some time.[1,2,3] These studies have dealt with both daytime and nighttime troughs. Although it was believed that the former were of an irregular and sporadic nature, recently it has been demonstrated[4] that the occurrence of daytime, high latitude, F-region troughs are not an occasional phenomenon but a rather stable, prevalent effect.

As far as mechanisms responsible for formation of these troughs is concerned, there is fairly general agreement that these are linked in some manner with the polar plasma convection pattern.[5] More specifically, however, it is still not clear which particular mechanisms contribute to which particular troughs. In general, several mechanisms have been, and still are, suggested as possible

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(Received for publication 31 January 1989)

1. Muldrew, D.B. (1965) F-layer ionization troughs deduced from Alouette data, *J. Geophys. Res.* **70**:2635.
2. Moffet, R.J. and Quegan, S. (1983) The mid-latitude trough in the electron concentration of the ionospheric F-layer: A review of observation and modeling, *J. Atmos. Terr. Phys.* **45**:315.
3. Roble, R.G. (1983) Global dynamic models of the earth's thermosphere and ionosphere, *ESA J.* **7**:405.
4. Whalen, J.A. (1987) The daytime F-layer trough observed on a macroscopic scale, *J. Geophys. Res.* **92**:2571.
5. Sojka, J.J., Raitt, W.J., and Schunk, R.W. (1979) Effect of displaced geomagnetic and geographic poles on high-latitude plasma convection and ionospheric depletions, *J. Geophys. Res.* **84**:5943.

candidates.[6] The two most notable of these are transport per se and a chemical effect that is in turn induced by transport. In the former, plasma produced at one location is transported from one region to another, retaining its original properties to some extent; in the latter, the convection of plasma relative to the neutral gases results in changes in chemical reaction rates.

In this report, we present calculations and arguments that indicate that chemical effects are unlikely to contribute substantially to the formation of the observed high latitude, daytime troughs.

2. ION CHEMISTRY

The chemical reaction with which we are primarily concerned is

$$O^+ + N_2 \rightarrow NO^+ + N \tag{1}$$

with the reaction rate k_1. This is one of the two dominant chemical loss reactions in the region of the F2 peak, where trough formation is observed. The other major reaction

$$O^+ + O_2 \rightarrow O_2{}^+ + O \tag{2}$$

with reaction rate $k_2 \cong 10k_1$ at 1000°K has a neutral reactant density $n[O_2] \leq 0.1\ n[N_2]$. More important, the reaction rate k_2 changes only moderately with temperature compared to Reaction (1). (See Figure 1, based on the expressions developed by St. Maurice and Torr.[7]) Thus, we will confine our attention to the reaction Eq. (1), as the most likely candidate for contribution to trough formation.

The reaction given by Eq. (1) does not decrease the overall charged particle number density. However, $NO^+ + e^- \rightarrow N + O$ has a rate constant of the order of 2×10^{-7} cm^3/sec so that the time constant for dissociative recombination is of the order of 1 minute. Since this is much shorter than the time constant for the reaction of Eq. (1), we may equate the latter with the loss of charged particles.

3. THE EFFECTIVE TEMPERATURE

Reaction rates are commonly given in terms of an effective temperature[1]

$$T_{eff} = \frac{m_i}{m_i + M_n} T_n + \frac{M_n}{m_i + M_n} T_i + \frac{m_i M_n}{m_i + M_n} \frac{u^2}{3k} \tag{3}$$

Here m_i and M_n are the ion and neutral reactant masses respectively, T_i and T_n are the ion and neutral temperatures, u is the difference in ion and neutral velocities, and k is the Boltzmann constant. For reaction (1) $m_i \cong 16$ amu, the mass of O^+, and $M_n \cong 28$ amu, the mass of N_2.

A variety of expressions have been used for T_{eff}, but none are appropriate to the problem at hand. The reason for this is that we do not have a steady state, but rather a dynamic one: through corotation,

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6. Grebowsky, J.M., Taylor, H.A., Jr., and Lindsay, J.M. (1983) Location and source of ionospheric high latitude troughs, *Planet. Space Sci.* **31**:99.
7. St. Maurice, J.P. and Torr, D.J. (1978) Nonthermal rate coefficients in the ionosphere: The reactions of O^+ with N_2, O_2, and NO, *J. Geophys. Res.* **83**:969.

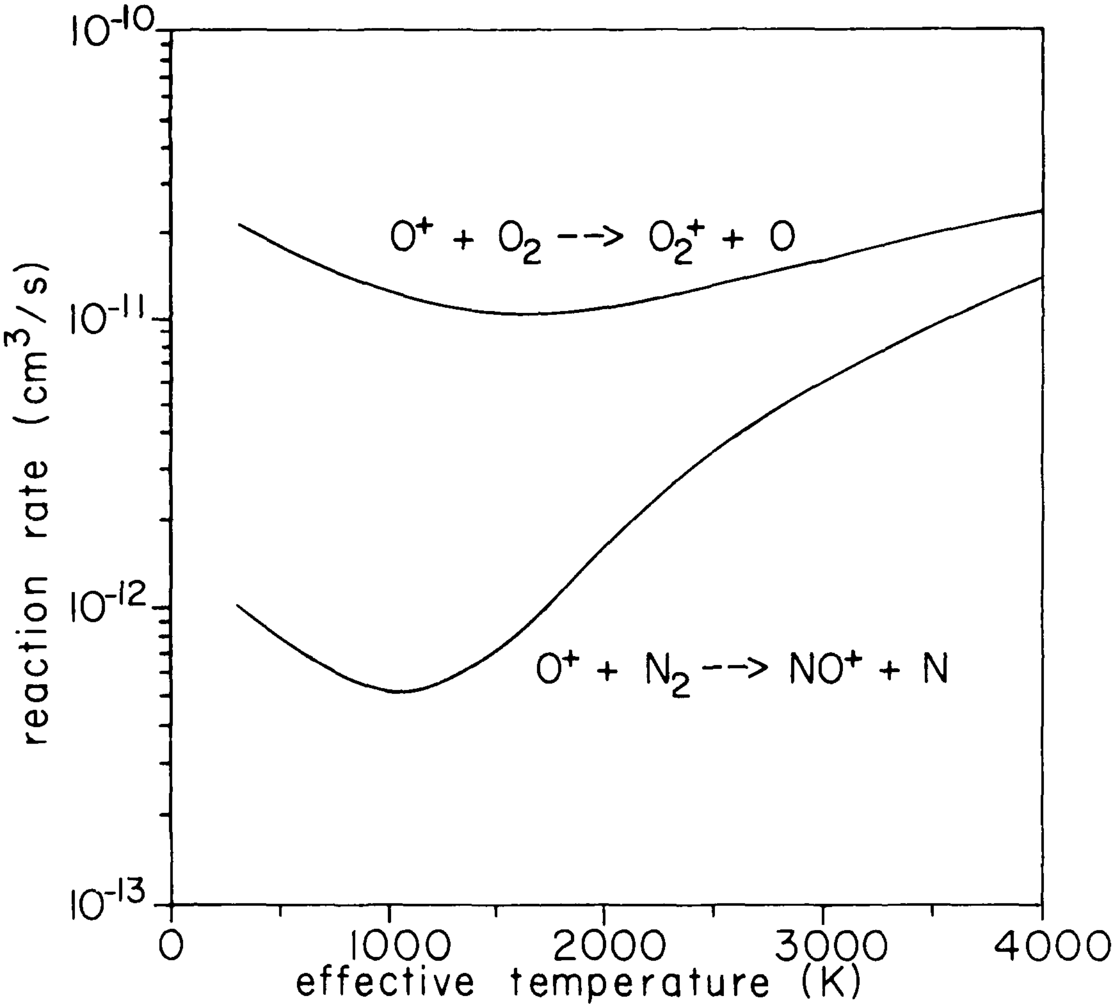

Figure 1. Comparison of the Temperature Dependence of the Two Main Reactions Controlling the Peak O^+ Density in the F-Region. The calculations are based on the formulas given in St. Maurice and Torr.[7]

a given locality enters the polar convection pattern, and then interacts with a changing ion velocity. The neutral velocity as well as both temperatures are then determined by the governing differential equations. Since the two time constants involved, that for change in moving through the convection pattern, and that for energy or momentum exchage between neutrals and ions in the F-region are both of the same order (hours), a solution of the differential equations is required to find the effective temperature.

We imagine the ion velocity, u_i, to be given by the polar convection pattern and, in accordance with some polar convection model[8] focus our attention on the center of the pattern, where the electric fields and velocities rise to their maximum values. This portion is linear, and as a given region corotates under the pattern, we assume the convection velocity rises linearly at a rate α (m/sec^2). The three equations for u_n (neutral velocity), T_i, and T_n are the neutral momentum, ion energy and neutral energy equations:

$$\frac{du_n}{dt} = -\nu_{ni}(u_n - u_i) \tag{4}$$

$$\frac{3}{2}k\frac{dT_i}{dt} = \frac{m_i\nu_{in}}{m_i + m_n}\left[3k(T_n - T_i) + m_n(u_i - u_n)^2\right] \tag{5}$$

$$\frac{3}{2}k\frac{dT_n}{dt} = \frac{m_n\nu_{ni}}{m_i + m_n}\left[3k(T_i - T_n) + m_i(u_i - u_n)^2\right] \tag{6}$$

In addition, the expression for $u_i(t)$ is

$$u_i(t) = \alpha t \tag{7}$$

In these equations, ν_{in} and ν_{ni} are the ion-neutral and neutral-ion momentum transfer collision frequencies, respectively, and m_n is the mass of the dominant neutral species (atomic oxygen at the F_2 peak). Note that here, $m_n \neq M_n$. Eq. (4) is the momentum equation for neutral particles, Eq. (5) is the energy equation for ions, and Eq. (6) is the energy equation for neutrals. Note that ν_{in} and ν_{ni} are related by

$$n_i m_i \nu_{in} = n_n m_n \nu_{ni} \tag{8}$$

For the F-region peak and topside, the relevant collision frequency is O^+ (the dominant ion) with O (the dominant neutral), and the dominant collision process is resonant charge exchange. Consequently, the collision freqencies ν_{in} and ν_{ni} have a temperature dependence approximately proportional to the square root of the relative temperature, $Tr \equiv (T_i + T_n)/2$. However, we have found from numerical integration of Eqs. (4) - (6) that the effect of this temperature dependence is small and can be neglected for present purposes. In the following analysis the momentum transfer collision frequencies are assumed to be constant.

Define $\nu \equiv \nu_{ni}$, $\tau \equiv 2\nu t$, and $u_n(0) = 0$. Solving Eq. (4) using Eq. (7), we obtain

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8. Sojka, J.J., Rasmussen, C.E., and Schunk, R.W. (1986) An interplanetary magnetic field dependent model of the ionosphere convection field, *J. Geophys. Res.* **91**:11281.

$$u_i - u_n = \frac{\alpha}{\nu}\left(1 - e^{-\tau/2}\right) \tag{9}$$

Let $\mu \equiv m_i/m_n$, $\rho \equiv \nu_{in}/\nu_{ni} = n_n m_n/n_i m_i$, $T_0 \equiv T_n(0)$, $K \equiv m_i\alpha^2/3kT_0\nu^2$, $\tilde{T}_i \equiv T_i/T_0$, and $\tilde{T}_n \equiv T_n/T_0$. Then using Eqs. (7) and (9) in Eqs. (5) and (6), we obtain

$$\frac{d\tilde{T}_i}{d\tau} = \rho\,\frac{\mu}{1+\mu}\left[(\tilde{T}_n - \tilde{T}_i) + \frac{K}{\mu}\left(1 - 2e^{-\tau/2} + e^{-\tau}\right)\right] \tag{10}$$

$$\frac{d\tilde{T}_n}{d\tau} = \frac{1}{1+\mu}\left[(\tilde{T}_i - \tilde{T}_n) + K\left(1 - 2e^{-\tau/2} + e^{-\tau}\right)\right] \tag{11}$$

These equations are exactly soluble in terms of elementary functions, but the details are cumbersome. Here, we make use of the facts that $\mu \cong 1$ and $\rho >> 1$ in the F-region. Then taking $\tilde{T}_n(0) = \tilde{T}_i(0) = 1$, we find

$$\tilde{T}_i(\tau) = 1 + K\tau - 2K(1 - e^{-\tau/2}) \tag{12}$$

$$\tilde{T}_n(\tau) = 1 + K\tau - 4K(1 - e^{-\tau/2}) + K(1 - e^{-\tau})$$

To lowest non-vanishing order in τ,

$$\tilde{T}_i(\tau) = 1 + \frac{K}{4}\tau^2 \tag{14}$$

$$\tilde{T}_n(\tau) = 1 + \frac{K}{12}\tau^3 \tag{15}$$

The difference in order is due to the ratio $\rho = \nu_{in}/\nu_{ni}$ being so large, which in turn is due to the fact that the gas is weakly ionized.

Putting Eqs. (9), (12), and (13) into Eq. (3) and setting $m_i = m_n = 16$ amu and $M_n = 28$ amu, we find

$$\tilde{T}_{eff}(t) = 1 + \frac{m_i\alpha^2}{33kT_0\nu^2}\left[22\nu t - 19 + 16e^{-\nu t} + 3e^{-2\nu t}\right] \tag{16}$$

The quantity in brackets is monotonically increasing with time, so the maximum value of T_{eff} is attained when $\alpha t_M = V_M$, the maximum value of velocity in the convection pattern.

$$\left(\tilde{T}_{eff}\right)_M = 1 + \frac{2m_i V_M^2}{33kT_0\nu^2 t_M^2}\left[22\nu t_M - 19 + 16e^{-\nu t_M} + 3e^{-2\nu t_M}\right] \tag{17}$$

Further, with regard to variations in ν, a maximum value of $[t_{eff}]_M$ is obtained for $\nu = 0$:

$$\left(\tilde{T}_{eff}\right)_{M_M} = 1 + \frac{14}{33}\frac{m_i V_M^2}{kT_0} \cong 1 + 0.4242\frac{m_i V_M^2}{kT_0} \tag{18}$$

while for $\nu t_M = 1$,

$$\left(\tilde{T}_{eff}\right)_M \cong 1 + 0.2816\frac{m_i V_M^2}{kT_0} \tag{19}$$

To convert Eq. (18) into one containing the electric field, we assume an ambient magnetic field of $B = 5 \times 10^{-5}$ T and obtain

$$\left(\tilde{T}_{eff}\right)_{M_M} = T_0 + 0.3265 E_M^2 \qquad (E_M \text{ in mV/m}) \tag{20}$$

Substitution of this expression into the expression for the reaction rate k_1 given by St. Maurice and Torr gives k_1 as a function of E_M. This functional relationship is illustrated in Figure 2 for $t_0 = 1000$ K.

4. CHANGES IN F_2 PEAK DENSITIES

To utilize Eq. (20) we need values of electric fields. Although values of fields in the polar ionosphere as high as, and occasionally higher than, 100 mV/m have been observed, such values are not common. Since the daytime troughs are observed over a broad range of solar activities, we examine models that give typical average values. In this, we have the recent work of Sojka et al[8] which provides a Kp dependent field model. In the dawn dusk plane, for the maximum value of the electric field, E_M, they find

$$E_M = \frac{60}{\pi} \frac{10 + 6.5Kp}{10 + 1.7Kp} \tag{21}$$

where the units of the field are mV/m. The value of E_M thus ranges between ~20 mV/m for Kp = 0 and ~50 mV/m for Kp = 7. Thus, for the largest average fields, the effective temperature for T_0 = 1000 K would be 1800 K, and k_1 would be $\sim 1.2 \times 10^{-12}$ cm^3/sec, a value ~2 times greater than the "undisturbed" value at 1000 K. If it is remembered that Eq. (20) is the maximum value to be expected, then factors of ~2 are the most to be expected in average enhancement of the reaction rate of interest. As will be seen, such increases lead to decreases in peak F_2 region densities much less than those actually observed. Fields of 100 mV/m, on the other hand, will produce an effective temperature of ~4200 K, and a value of $k_1 \cong 1.6 \times 10^{-11}$ cm^3/sec, which is ~30 times higher than the value at 1000 K.

Changes in F_2 peak densities induced by relative ionic motion may be studied in several ways. Schunk et al[9] insert the ion drift velocities, assumed to be constant, steady state values, directly into the conservation equations. They find that for an electric field strength of 50 mV/m, the F_2 peak density is reduced by a factor of 1.5 from the zero field value.

Alternatively, one can arbitrarily vary values of the rate constant k_1 and compute ion density profiles as a function of rate constant. The values of k_1 can then, via Figure 1, be associated with values of T_{eff}, and using Eqs. (19) and (20) with ion drift velocities and attendant fields. Such calculations have been made using the daytime ionosphere model described in Decker et al[10], the

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9. Schunk, R.W., Raitt, W.J., and Banks, P.M. (1975) Effects of electric fields on the daytime high-latitude E- and F-regions, *J. Geophys. Res.* **80**:3121.

10. Decker, D.T., Daniell, R.E., Jr., Jasperse, J.R., and Strickland, D.J. (1987) Determination of ionospheric electron density profiles from satellite UV emission measurements, in *The Effect of the Ionosphere on Communication, Navigation, and Surveillance Systems*, J.M. Goodman, ed., U.S. Naval Research Laboratory, Washington, pp. 685-694.

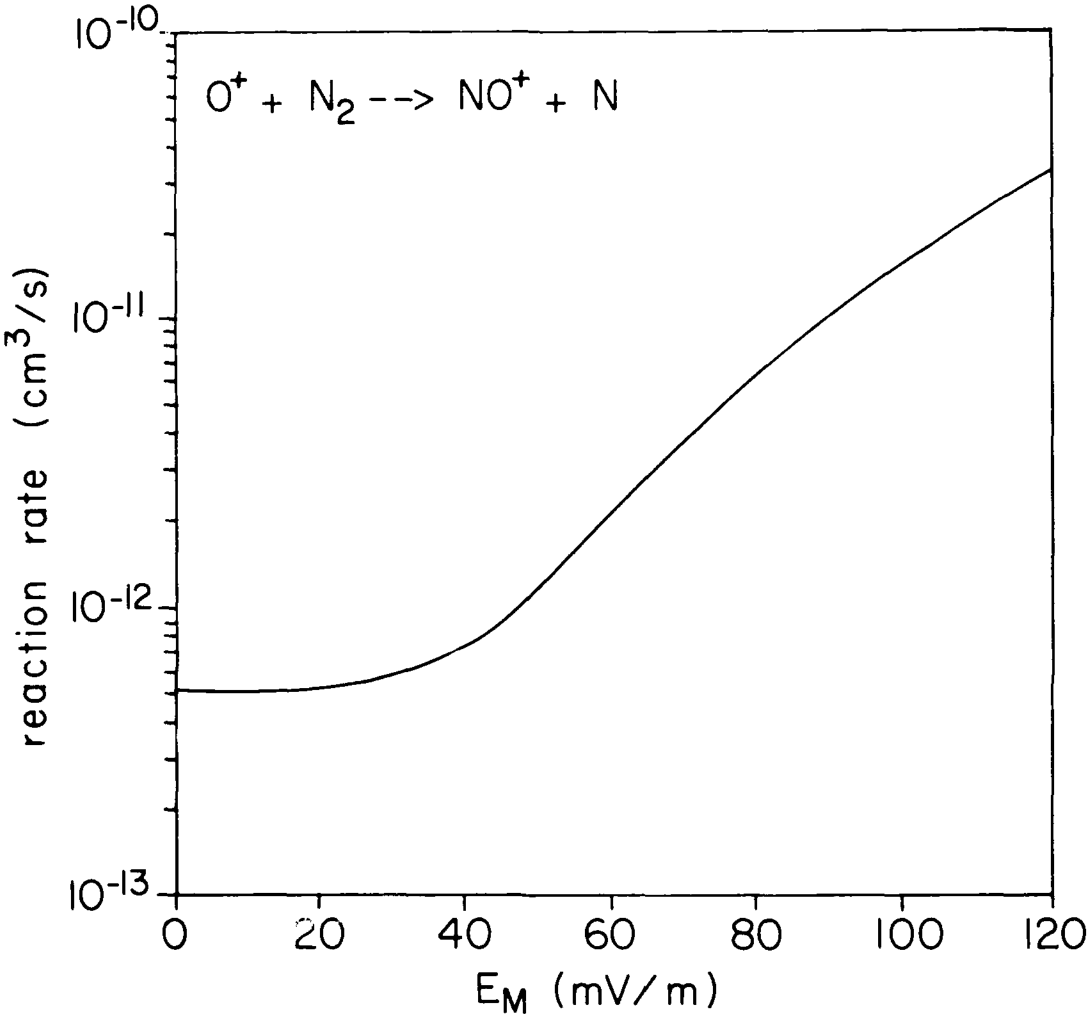

Figure 2. Rate coefficient for $O^+ + N_2 \rightarrow NO^+ + N$ as a function of E_M (maximum convection electric field) based on our Eq. (20) and the formulas of St. Maurice and Torr.[7] The calculations assume $T_0 = 1000$ K.

F-region portion of which is based on the model of Anderson.[11] Figure 3 shows density profiles for three values of k_1, 5×10^{-13}, 2×10^{-12}, and 10^{-11} cm^3/sec corresponding to T_{eff} values of 1000, 2100, and 3600 K or electric fields of 0, 60, and 90 mV/m, respectively. Noting the zero and 60 mV/m fields we see a decrease in F_2 peak values by a factor of ~1.75, in rough agreement with the decrease found by Schunk et al.[9] Even using the reaction rate corresponding to 90 mV/m results in a density reduction of only a factor of 4.

Whalen[4] finds decreases in the daytime trough to vary by factors of 3 to 10. Considering that Eq. (20) represents a maximum estimated value of T_{eff}, and further, that even using this maximum, model calculations do not produce changes of 3 to 10 in peak densities, it would seem that the chemical mechanism can make only a minor contribution to the daytime troughs observed by Whalen.

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11. Anderson, D. N. (1973) A theoretical study of the ionospheric F-region equatorial anomaly 1, Theory, *Planet. Space Sci.* **21**:409.

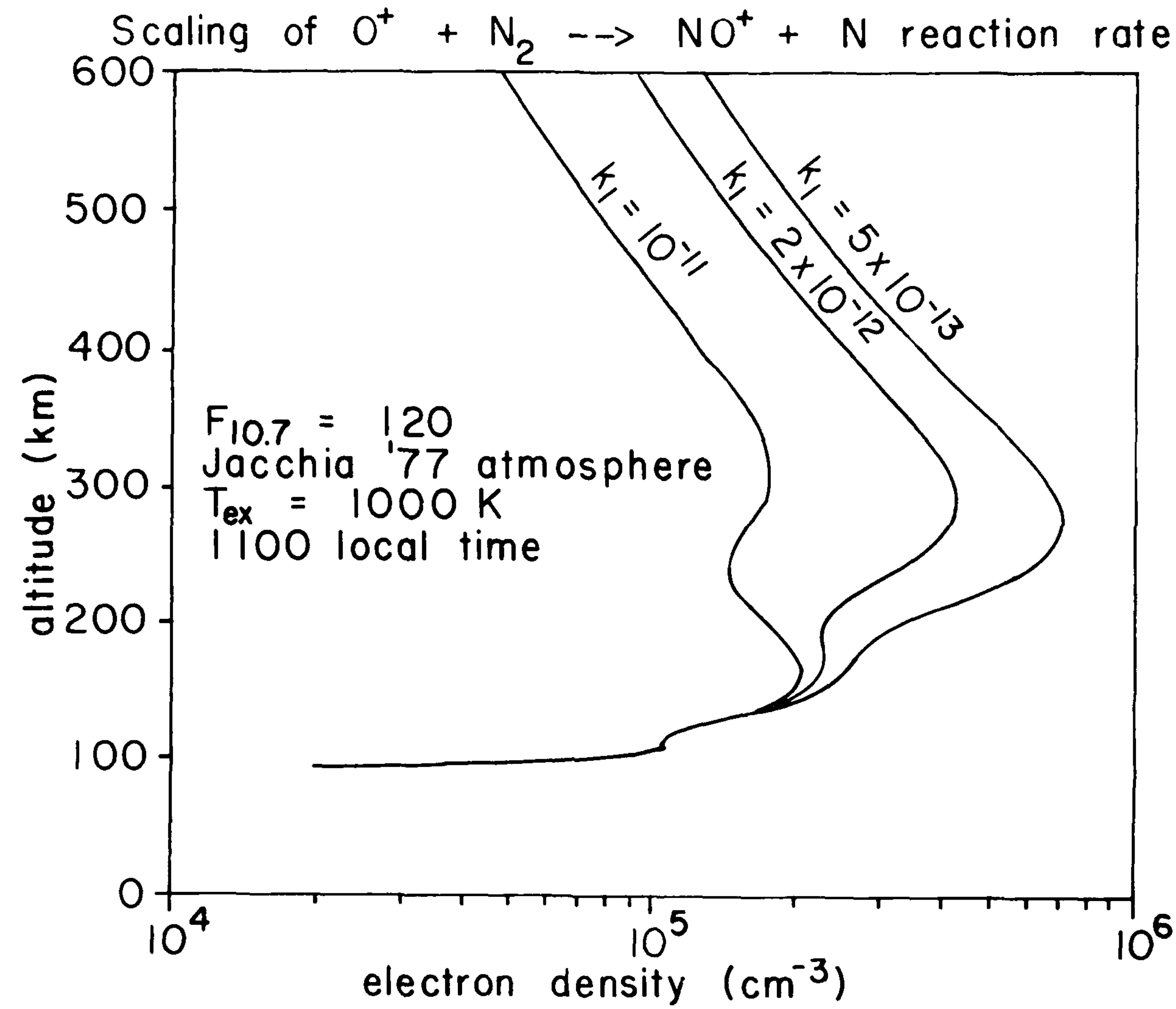

Figure 3. Electron Density Profiles for Three Values of the Rate Coefficient k_1 ($O^+ + N_2 \rightarrow NO^+ + N$). The calculations used a Jacchia[12] model atmosphere with an exospheric temperature of ~1000 K, and the solar EUV fluxes of Heroux et al[13] (for $F_{10.7} = 120$). The ionospheric model used for these calculations is described in Decker et al.

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12. Jacchia, L.G. (1977) Thermospheric Temperature, Density, and Composition: New Models, Smithsonian Astrophysical Observatory Special Report 375.

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